AD-A064 822   SHEFFIELD UNIV (ENGLAND) DEPT OF CHEMICAL ENGINEERIN--ETC   F/G 21/4
INVESTIGATIONS OF TURBULENT COMBUSTION.(U)
SEP 78   N A CHIGIER, A J YULE   AFOSR-77-3414

UNCLASSIFIED   AFOSR-TR-79-0053   NL

1 OF 1
AD
A064822

END
DATE
FILMED
4-79
DDC

AFOSR-TR- 79-0053

(13) LEVEL II

AD A064822

DDC FILE COPY

Contract/Grant Number AFOSR-77-3414

INVESTIGATIONS OF TURBULENT COMBUSTION

Report on initial research under contract 'Coherent Structures in Turbulent Flames by Laser Anemometry'.

Norman A. Chigier & Andrew J. Yule,
Department of Chemical Engineering and Fuel Technology,
University of Sheffield,
Sheffield, England.

30th. September, 1978.

Interim Scientific Report, 1 August 1977 - 1 August 1978.

Approved for public release; distribution unlimited.

Prepared for

Air Force Office of Scientific Research/NA, Bolling, AFB, Washington, D.C., 20332. U.S.A.

and

EUROPEAN OFFICE OF AEROSPACE RESEARCH AND DEVELOPMENT
London, England.

PREFACE

This report describes the first year's work on this research contract. The research, by its nature, requires new and precise measurement and data analysis techniques in carefully controlled flows with well-defined boundary conditions. Thus much of the work during the initial year of this research has involved the development of instrumentation and apparatus. This work is outlined with reference to publications. The initial results which have been obtained with the diffusion flame and spray experiments have also been of sufficient interest to be reported in the open literature. Experimental investigations of aspects of the diffusion flame structure has received financial support from the Office of Naval Research (Project SQUID), Sub-contract No. 8960-30. The Science Research Council, U.K., has recently provided finance for major items of equipment utilised in this research, i.e. a high speed camera and improved modules for the laser anemometry system.

1. INTRODUCTION

The objective of this research is to obtain increased understanding of turbulent combustion in flows related to propulsion systems. The specific approach of the study is to quantify the roles of large eddies (coherent structures) in these flows; for example their relation to interface burning regions, residence times, macro and micromixing, and droplet vaporization and burning in fuel sprays. Precise measurement techniques, with good spatial and temporal resolution, must be utilized to permit the specialized conditional sampling and correlation, data processing techniques which are required for this 'coherent structure' approach. Thus particular emphasis has been placed on the development of measurement techniques, particularly laser anemometry, micro-thermocouples and ionization probes. Ultimately the signals from combinations of these probes will be simultaneously acquired by computer to enable specialized and novel data processing techniques to be applied to measure the structures and histories of the large eddies and the interface burning regions associated with them. For this fundamental investigation it is considered of great importance that the boundary conditions of the flows studied are known precisely and are carefully controlled. This is essential, both from the point of view of comparisons with flow modelling approaches and to enable unambiguous interpretation of data. Thus considerable effort has been expended initially on the design of the apparatus to achieve this aim.

The investigation concentrates on three main areas:

(1) The structure of an axisymmetric diffusion flame, in a low velocity secondary flow, developing from laminar initial conditions.
(2) The structure of turbulent fuel sprays: This utilizes a novel laser anemometry technique for simultaneously measuring droplet sizes and velocities.
(3) A flow visualization investigation, using high speed cine-photography, of the above flows and also of a range of other flows, e.g. a flame impinging on a flat plate.

These aspects are described in more detail below and fuller accounts will be found in the papers referenced.

2. DIAGNOSTIC TECHNIQUES

During the first year of research emphasis has been placed on the development of three main measurement techniques which will permit the objectives of the investigation to be met:

Laser Doppler Anemometry (LDA)

The LDA system has been developed, firstly, to improve its accuracy for real time velocity measurement in diffusion flames, and secondly, to permit simultaneous measurement of droplet sizes and velocities in spray flames.

Velocity Measurement

A forward scattering, 1 watt, Argon-Ion laser anemometer is used. A counter-processor, developed in the Department, is interfaced with a PDP-8E computer and a PDP-1103 microprocessor. During the last year the optical qualities have been improved by the instalment of a TSl beam splitter. A Bragg cell unit has also been purchased. Off axis light collection, at an angle of 7^{o}, is used with a slit aperture to minimise the measurement volume dimensions. An extensive, and continuing, series of tests has been carried out to maximise the accuracy of measurements of instantaneous velocity. The signal processing and high level validation logic have been extended and improved. A double counter is used, which counts and compares the velocities from two sets of fringes. Logic gates are operated from both the AC signal and the pedestal. 'Bad' signals are also recognised and rejected by their positions in the velocity probability distribution. The LDA has been developed and its performance calibrated by using signals produced by a rotating disk and by comparison with hot wire data for cold flow experiments. Velocity can be measured with better than 1% accuracy. The maximum velocity counting rate, of 2kHz at flow velocities of the order 10 ms^{-1}, is found to be limited by the maximum seeding levels which can be utilized, which are themselves limited by fluid dynamic and light scattering considerations.

Particle Size Measurement

The authors have described[1] a technique for simultaneous measurement of particle sizes and velocities by measuring the peaks of the pedestal signals produced by particles crossing the LDA measurement volume. This work has continued during the last year, under AFOSR support, and the use of various LDA optical geometries has been studied and reported.[2,3] At the 17th. International Combustion Symposium the authors[4] described the application of the technique to a kerosene spray flame. The development and proving stage of this technique has now ended and work has begun on its application to study the structure of turbulent fuel sprays. In brief, single and joint probability distributions of signal peak and velocity, derived from several thousand fuel droplets, are converted to droplet size distributions and size-velocity correlations by using light scattering analyses, backed up by calibrations using a TSl monosize particle generator. Particles can be measured in the range of, at least, 15 $\mu m \leqslant d \leqslant 300$ μm and with number densities up to 10^{10} m^{-3}. The major restrictions are that the particles should be near-spherical and with known optical properties.

Micro-Thermocouples.

The micro-thermocuple technique has been developed to permit point measurements of fluctuating temperature with accuracy up to at least 2kHz. Emphasis has been placed upon computer processing of signals with the aim of simultaneously acquiring signals from several thermocouples and also from combinations of thermocouples and other probes; to permit, for example, velocity-temperature cross-correlation measurement. The authors have reported[5] on the use of a computer interfaced thermocouple and have described the new technique for measuring thermocouple time constant in situ in flames: A square wave overheating current is applied to the thermocouple. The temperature decay

curve after each pulse is acquired and ensemble averaged over several hundred pulses. The fluctuations caused by flame temperature fluctuations are thus averaged out and the resulting smooth decay curve is used to derive a value for the time constant and to indicate variations from the first order compensation assumption. Techniques have been developed for manufacturing thermocouples from Pt - Pt/13% Rh wires and also Pt/20% Rh - Pt/40% Rh wires. Diameters used depend upon flame conditions, and range from 25 μm to 75 μm.

Ionization Probe

A flame ionization probe has been constructed and tested. The probe consists of a 1 mm length of exposed Pt electrode formed from the end of a Pt wire which runs the length of a coaxial water cooled stainless steel tube. On application of a potential of 20V between the central electrode and the outer tube, a current flows which is a function of the ionization level in the close vicinity of the electrode. Although an 'intrusive' probe the technique has the advantage of a very high frequency response and it is ideally suited for the detection of interface burning regions. The use of the signal as a trigger for conditional sampling of eddy/interface structure is being investigated.

Flow Visualization/Photography

A 'Hadland' high speed camera has been purchased. This is capable of a framing rate of up to 10,000 pps. It has the important facility for superimposing probe signals on film so that observed structures can be correlated with simultaneously acquired point measurements.

The camera is used to observe flames directly and also by using Shadowgraph and schlieren techniques. A large schlieren system, using 600 mm diameter mirrors, has been set up to investigate the diffusion flame experiment.

A 'Polaroid' technical camera and a double spark unit have been set up on three dimensional traversing units for investigations on the fuel spray apparatus.

A Quantimet image analysis computer[6] is used to analyse photographs of sprays, as reported by the authors.

Digital Signal Processing

The aims of the investigation require particular emphasis on digital signal acquisition techniques. Various interfaces have been constructed for the different techniques described above. Programmes have been developed for the acquisition of signals and the derivation of probability distributions, spectra and correlations. In particular, when very large numbers of signals are required, a PDP 1103 and 8E computer have been combined in a "buffer" system so that the disk of the 8E can be filled with data, essentially without a break.

3. APPARATUS

Diffusion Flame Experiment

Apparatus has been constructed which produces an axisymmetric flame from a 25.4 mm diameter nozzle, surrounded by a 400 mm diameter secondary air flow (as described by the authors in Ref. 7.) Great effort has been exerted to achieve laminar boundary layers, uniform velocity profiles and low (< 1%)

turbulence levels in the nozzle and secondary flows. These requirements were found to be difficult but not impossible, to satisfy, because of the particular problems produced by the high density of seeding particles in the flows required for LDA measurements. The LDA system is fixed and the complete nozzle and secondary flow assembly is traversed radially and axially. The primary nozzle flow is propane with some air (carrying seeding particles).

Fuel Spray

An atomiser is positioned at the lower end of a coaxial vertical duct of 275 mm diameter. The gas flow conditions in this duct can be varied from laminar, cold uniform flow to either laminar or turbulent heated or vitiated flow. This apparatus permits the study of vaporizing or burning sprays with carefully controlled boundary conditions. The apparatus has facilities for investigating up to 1 m lengths of spray using spark photography, thermocouples and sampling probes. Work is in progress to guide the LDA beams into this rig to permit simultaneous particle size and velocity measurements.

4. EXPERIMENTAL RESULTS

Diffusion Flame

The initial experiments are concentrating on studying one flame in detail, with emphasis, firstly, on determining the initial conditions and the development of the turbulent flame in the transition region near the nozzle (see Ref. 7.) The experiments are comparing the structure of this transition region for the cases of burning and non-burning versions of the same initial flow. It is considered important to understand this relatively orderly vortex-flow before studying the 'fully turbulent' downstream flame in detail. This is because the turbulent flame is dependent on the initial conditions, for example flow visualization shows that interface burning regions associated with vortices in the transition region can still be identified far downstream in the turbulent flame. This has important repercussions from the point of view of residence times and pollutant formation. Measurements of temperature, velocity and vortex passing frequencies have been made in the transition region with $U_j = 6.3$ m/s, $Re = 10^4$ and $U_s = 0.73$ m/s. The fuel/air equivalence ratio of the propane/air premixed flow is 10.4 and the total visible flame length is approximately 1.5 m.

The major physical processes of vortex formation and coalescence in the initial region of mixing layers of jets appear to be similar for cold and burning conditions. In both cases, wave instabilities develop in the laminar flow and vortices are formed which have significant periodicity. Coalescence of distorted vortices results in the establishment of turbulent flow and this can be identified by high-speed cine photography and from major power spectra. For Re of 10^4, coalescence in the flames occurs between 16 and 20D, compared with $x < 2D$ under non-burning conditions. Regions of flame luminosity indicate that reaction is occurring predominantly at interfaces which bound individual vortices. Wave instabilities in vortices are identified by luminous axial streaks. The luminous streaks mark the azimuthaly distributed troughs of ring vortices and are caused by quenching and/or oxygen starvation. Approximately 12 waves are seen to form around the circumference of the flame but the number of waves (and streaks) is a function of the Reynolds number. Downstream of transition detached islands of flame can be seen to be extinguished, due to detached fuel eddies, local quenching and local oxygen starvation.

Significant differences are measured in vortex passing frequencies and Strouhal numbers for burning and non-burning conditions. The high values of

St between 1 and 2 in the first 2D of the non-burning jet are not detected under flame conditions. For the particular flame studied St is 0.4 at 8D and decays to 0.15. Coalescence is random in both cases but, in the flame, separation distances are larger, resulting in lower vortex passing frequencies.

Combustion causes temperature, density, viscosity, conductivity and molecular diffusion changes of the order of one magnitude. Buoyancy forces are generated, due to density differences and density change results in expansion, which must manifest itself in radial expansion and/or acceleration, so as to accommodate the increased volumetric flow rate. The results obtained so far from the present study suggest that the changes in kinematic viscosity have been the most important factor in the transitional flame in the very significant changes seen at $Re = 10^4$. The initial region is stretched in the axial direction from 3D to 20D. The potential core length is increased and the rate of growth of the mixing layer is reduced. This stretching is not due to increased convection speeds, but is caused by the delay in the establishment of turbulent flow. The fundamental mechanisms of potential flow, causing the roll-up of the interface, remains but, through the action of increased kinematic viscosity, instabilities are damped. The net effect is roughly equivalent to reducing the Reynolds number. The detailed mechanisms of vortex growth and the physical structure of mixing layers in flames are now being investigated in much greater detail using the cross-correlation and conditional sampling techniques required for studies of coherent structures.

Fuel Sprays

The authors have described[3,4] the application of the LDA particle sizing technique to measure droplet size distributions and size-velocity correlations in a kerosene spray. Temporal size distributions were measured at the same positions under burning and non-burning conditions. Comparison of distributions, in terms of local liquid phase volume flux as a function of diameter, showed clearly the preferential vaporization of smaller droplets. Size - velocity correlations clearly demonstrated a variation in the local average velocity for droplets, as a function of droplet diameter. By assuming that the smaller droplets move with the local gas velocity, averaged local droplet Reynolds numbers can be derived as a function of droplet diameter. The variance of droplet velocities was found to be higher for the smaller droplets, which is expected as, the smaller the droplet, the more closely it should follow the turbulence fluctuations.

Flow Visualization

In addition to obtaining films of the flows outlined above, the authors have established a 'library' of films of combustion flows, with concentration on the identification of the larger eddies and coherent interface burning regions. Films of a diffusion flame impinging on a flat plate have been taken for various initial conditions. These clearly show the formation of vortex ring eddies and their subsequent breakdown into three-dimensional eddies.

5. CONCLUDING REMARKS

During the first year of research instrumentation techniques and apparatus have been developed for the measurement of turbulence structure in diffusion flames and fuel sprays, with emphasis on the rules of the large eddies and coherent interface burning regions. The initial experiments have clearly demonstrated the importance of large scale structure, its development from transitional structures and the interaction between combustion and the formation of these structures. The new LDA system has clearly demonstrated the interaction between the turbulent gas flow and the droplets in the fuel

spray. Work is now in progress:

(i) In the diffusion flame, to more fully map the transitional flame and also the downstream turbulent region. Emphasis will be placed on simultaneous measurements by several probes, to permit conditional sampling comparisons with flow visualizations and comparisons between burning and non-burning flows.
(ii) In the fuel sprays, a systematic investigation of spray structure using the new measurement techniques.

REFERENCES

1. Yule, A.J., Chigier, N.A., Atakan, S. & Ungut, A. "Particle size and velocity measurement by laser anemometry." AIAA J. Energy, 1, 220-228, July 1977.

2. Ungut, A., Yule, A.J., Taylor, D.S. & Chigier, N.A. "Simultaneous velocity and particle size measurements in two-phase flows by laser anemometry". Paper 78-74, AIAA 16th. Aerospace Sciences Meeting, Huntsville, Alabama, Jan. 1978. To be published, AIAA J. Energy.

3. Chigier, N.A., Yule, A.J. & Ungut, A. "Particle sizing in flames with laser velocimeter". Proc. of 3rd. Int. Workshop on Laser Velocimetry, Purdue University, July, 1978, Hemisphere Press, 1979.

4. Chigier, N.A., Ungut, A. & Yule, A.J. "Particle size and velocity measurement in flames by laser anemometer". Proc. of 17th. Int. Symp. on Combustion, University of Leeds, August, 1978, Combustion Institute, Pittsburgh.

5. Yule, A.J., Taylor, D.S. & Chigier, N.A. "Thermocouple signal processing and on-line digital compensation". AIAA J. Energy, 2, No.4, pp.223-231, July, 1978.

6. Yule, A.J., Cox, N.W. & Chigier, N.A. "Measurement of particle size in sprays by the automated analysis of spark photographs". Particle Size Analysis, pp. 61-73, Heyden Press, London, 1978.

7. Chigier, N.A. & Yule, A.J., "The physical structure of turbulent flames". To be presented at AIAA 17th. Aerospace Science Meeting, New Orleans, Jan. 15-17, 1979.

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFOSR-TR-79-0053	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): INVESTIGATIONS OF TURBULENT COMBUSTION	5. TYPE OF REPORT & PERIOD COVERED: INTERIM Rept. 1 Aug 77 — 1 Aug 78
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): NORMAN A. CHIGIER, ANDREW J. YULE	8. CONTRACT OR GRANT NUMBER(s): AFOSR-77-3414
9. PERFORMING ORGANIZATION NAME AND ADDRESS: UNIVERSITY OF SHEFFIELD, CHEMICAL ENGINEERING & FUEL TETCHOLOGY DEPARTMENT, SHEFFIELD, S13JD, England	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 2308A2, 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS: AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA, BLDG 410, BOLLING AIR FORCE BASE, D C 20332	12. REPORT DATE: Sep 78
	13. NUMBER OF PAGES: 7
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): 9p.	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

COMBUSTION, TURBULENCE, INSTRUMENTATION, COHERENT STRUCTURES, EDDIES, FUEL SPRAYS, LASER ANEMOMETRY

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The aim of the research is to increase fundamental understanding of turbulent combustion in gas diffusion and spray flows related to propulsion systems; with particular emphasis on the roles of large eddies (coherent structures) in the turbulence. It is discribed how this objective requires the development of high resolution measurement techniques. Techniques are discribed for the measurement of particule size and velocity by laser anemometer, temperature by computer interfaced thermocouples and flame ionization by ionization probes. The initial results of the investigation are described for the two major areas; axisymmetric

diffusion flows and fuel sprays. The importance of the initial, near field, region of the diffusion flame is described with emphasis on the influences of heat release in the transitional flow. The initial research with fuel sprays, using leaser anemometry, shows the importance of being able to measure gas velocity, particle velocity and particle size, simultaneously. This permits derivation of temporally averaged size distributions and turbulence-droplet interaction.